An Efficient Sub-Gigawatt Level X-band BWO at Low Guiding Magnetic Field

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Abstract—Efficiency enhancement in Backward Wave Oscillator (BWO) device at low magnetic field is a matter of concern. With decrease in guiding magnetic field, the quality of beam gets reduced along with increase in transverse motion of electrons. The transverse motion of electrons extracts energy from the RF field and undergo multipacting with the Slow Wave Structure (SWS) surface under influence of periodic accelerating electric field of microwaves. Hence, electron beam to microwave conversion efficiency gets reduced. Lowering magnetic field can also lead to two types of cyclotron absorptions i) Forward cyclotron absorption & ii) Backward cyclotron absorption. The simulation results of High-Power Microwave (HPM) generation from a non-uniform X-band BWO device having circular profiled SWS have been presented in this paper. Output power of 810 MW has been observed at 9.8 GHz with 27% efficiency, guided by 0.6T magnetic field. Also, overbunching & backstreaming of electron beam was observed in PIC simulation using CST studio. These phenomena restrict the device efficiency.

Keywords—Backward Wave Oscillator, Slow Wave Structure, Overbunching, Cyclotron Absorption.

I. INTRODUCTION

High Power Microwave (HPM) devices have broad applications in many fields of science and engineering like plasma heating, material processing, high resolution RADARs and many strategic applications [1,2]. Backward wave oscillator (BWO) is a device used to efficiently convert the electron kinetic energy into electromagnetic radiation at microwave frequencies [3]. BWO is preferred among all HPM devices due to its wide range of frequency tunability and high spectral purity.

In BWO, the electron beam is guided by an axial magnetic field through a cylindrical cavity having Slow Wave Structure (SWS). The beam interacts with the normal modes of SWS having phase velocity parallel with the beam velocity throughout the interaction length. This synchronism is known as Cerenkov synchronism [1-4]. This interaction leads to certain instability that transfers energy from beam to electromagnetic wave field. In BWO, the instability type is absolute where as in Travelling Wave Tube (TWT), it is convective type [5].

In order to guide electron beam inside the SWS a high magnetic field is either provided by solenoid or by superconducting magnets. To save the refrigerating cost and energy consumption by electromagnet, it is very important to reduce the magnetic field to the levels attainable by permanent magnets. Also, use of permanent magnet can increase the repetition rate of the whole HPM system, thereby increasing the average output power [6].

BWO devices can operate for generation of multi-Gigawatt level peak power at low magnetic field and peak experimental microwave power in excess of 7.6 GW has been realized with 42% efficiency [7]. However, these devices are highly overmoded, having cross section diameter to operating wavelength ratio in between 1 & 2 or more [6-10]. The overmoded structure has an advantage of increased power handling capability. Limiting factors in these devices is the mode competition which limits the microwave conversion efficiency for a desired mode [7,8]. Devices having normal cross sections do suffer from pulse shortening and field breakdown at much lower levels of peak microwave power [11,12]. These normal cross section devices do have advantage in terms of mode competition, compact size and ease of designing magnetic field system. Furthermore, the use of weak magnetic field solves the problem of collector heating as the beam energy deposition area increases for low magnetic field [13].

In multi-Gigawatt BWO devices, RF field inside the electrodynamic structure becomes strong enough to cause electron emission from the inner surface of conducting material by field emission mechanism [11,12]. Field emission electrons get accelerated under the influence of generated...
microwave field and hit the SWS surface with certain amount of kinetic energy. This results in emission of secondary electrons from the SWS surface. Thus, a local electron stream is formed which keeps impacting the SWS surface. Path of electron stream is along the local electric field inside the SWS due to presence of weak magnetic field. The electron stream heats up the SWS surface and leads to plasma formation [11]. This plasma formation limits the device efficiency and shortens the microwave pulse duration. To avoid field breakdown, circular corrugated non uniform SWS is used for beam-wave interaction.

An attempt has been made to boost the overall HPM system efficiency and this whole process depends upon how you design and optimize the beam-wave interaction region, the SWS. To improve the efficiency, two approaches have been implemented. The first is by shortening the SWS period along beam downstream in accordance with appropriate beam wave synchronization and the second is by employing a smooth semicircular wall to increase the electric field limit within SWS. Additionally, the paper used simulations to assess the difficulties encountered during this process. Operational challenges with low magnetic field such as beam divergence, back streaming are also taken into count. Optimizations of SWS have been done in compliance with References 14 & 15.

### II. Model Description

The schematic of the overmoded X-band BWO is shown in Fig. 1. The SWS average diameter to free space wavelength of microwave is kept 1.6 \((D/\lambda)\). The electron beam is emitted from an annular cathode and is faint modulated at Resonant Reflector (RR). Here, RR act both as reflector for backward wave and pre-modulation cavity.

The dispersion curve for semi-circular SWS with a period of 12 mm and average radius of 24 mm is shown in Fig. 2. The electron beam interacts with the synchronous TM\(_{01}\) mode at 9.8 GHz frequency. The beam line and interaction point with cold structure mode is also shown in the figure (Point A).

### III. Theoretical Background

For beam wave interaction, the phase velocity should match with the electron beam velocity. These formulations are governed by the actual physical processes happening inside the interaction region under the influence of high electric field of generated microwave. These formulations are mentioned in the following sections.

#### A. Beam Wave Interaction

HPMs are generated by transferring the kinetic energy of moving electrons to the electromagnetic energy of the microwave fields due to the interaction of the SWS Eigen modes with the natural electron beam modes of oscillations. The two modes of oscillations exist almost independent of each other except certain values of frequency, for which they exchange energy resonantly [16]. The dispersion curve corresponding to the SWS and electron beam, depicting the resonance interaction (Point A) shown in Fig. 2.

Now, for the stable transportation of electron beam from cathode through SWS up to the beam dump region, the guiding magnetic field strength ‘\(B\)’ should meet the following condition [17].

\[
B \geq \left(\frac{2\pi m e}{\epsilon_0 m^*}\right)^{1/2}
\]

Where, \(n_e\) is the electron number density of the beam, \(m\) and \(\gamma\) are the rest mass and relativistic factor of electron respectively, \(\epsilon_0\) is the dielectric constant in vacuum.

It is obvious that, for a certain amount of current, if the diameter of the cathode increases, the electron number density decreases, which leads to decrease in space charge effect and hence, leading to proper stable transportation of beam at lower magnetic field strength. But lower magnetic field operation introduces cyclotron absorption which restricts the device efficiency. There are two types of cyclotron synchronism [18]. One is the electron beam cyclotron mode synchronizes with the fundamental spatial harmonic of backward wave and other is when it synchronizes with the fundamental spatial harmonic of forward wave. These two field strengths were calculated and given below respectively \((B_{res1} \text{ and } B_{res2})\) [18].

\[
B_{res1} = \frac{\gamma m e c}{\epsilon} \frac{2\pi}{z_0}
\]

\[
B_{res2} = \frac{2\gamma m e c}{\epsilon} \left(\frac{\pi}{z_0} - k^*\right)
\]

Here, \(c\) is the speed of light in vacuum, \(e\) \& \(\beta\) are the charge and relativistic factor of electron, \(z_0\) is the period of SWS and \(k^*\) is the wave number corresponding to forward mode.

In spite of different transverse modes, it is important to know the interaction of beam with the axial modes of electromagnetic wave. The axial mode generally referred to...
the phase difference of electromagnetic wave between two consecutive unit cells of SWS. Operation mode is chosen to be near π-mode because of its higher Q-factor and lower starting current [19,20]. Exact π-mode operation is not possible as the group velocity of microwave is zero, thereby the wave behaves as standing wave and the energy will be stored inside the cavity that cannot be extracted.

There is another aspect of near π-mode operation which makes the low magnetic field operation region wider (Refer to the Equation 2).

![Figure 2. Dispersion of SWS with Beam Interaction Point](image)

**B. Design of SWS**

From the Fig. 2, it is clearly shown that at point A, the phase velocity matches with the beam velocity. Therefore,

\[ v_p = v_b \]  

Putting, \( v_p = \frac{\omega}{k} \), \( v_b = \beta c \) and \( k = \frac{\Phi}{Z_0} \) in above equation, we can find the pitch or period of the SWS.

\[ Z_0 = \frac{\Phi v_b}{\omega} = \frac{\Phi \beta c}{2\pi f} \]  

Where, \( \Phi \) refers to axial mode of operation and \( f \) is the desired frequency of generated microwave. The beam velocity \( (v_b) \) can be calculated from beam current \( (I_b) \) vs gamma \( (\gamma_b) \) plot. For detailed explanation follow Ref. 3 and the beam current related with gamma by the following equation [3].

\[ I_b = \frac{I_0}{2 \text{Im}(\gamma_b/r_b)} (\gamma_b^2 - 1)^{0.5} \frac{\gamma_c - \gamma_b}{\gamma_b} \]  

Here, \( I_0 \) is the Alfven current, \( r_b \) & \( r_h \) is the average radius of SWS & beam radius respectively and \( \gamma_c = 1 + \frac{eV_0}{511} \). \( V \) is the input voltage in kV.

After the design of single unit cell of SWS, the starting current can be calculated for the periodic SWS operating in pure TM_{01} mode by the following equation [21,22].

\[ I_s = \frac{I_0}{2 \text{Im}(\gamma_b/r_b)} (\gamma_b^2 - 1)^{1.5} \left( \frac{\lambda}{L} \right) \times 1.974^3 \]  

Here, \( Z_n \) is the interaction impedance of \( n \)-th spatial harmonic, \( L \) is the length of SWS and \( \lambda \) is the desired wavelength of generated microwave.

\[ Z_n = \frac{|E_{bn}(\omega_p)|^2}{2k_n^2P} \]

Here, \( E_{bn}(\omega_p) \) is the axial electric field produced at beam position due to power \( P \) fed to the SWS and \( k_n \) is the propagation constant of the desired mode.

**IV. SIMULATION AND ANALYSIS**

Different components of BWO device have been simulated using CST (Computer Simulation Technology) studio. The Eigen Mode Solver (EMS) setup is used for designing the number of unit cells to be used in the SWS. Time Domain Solver (TDS) setup is used for estimating the frequency that can be hold in the finite size SWS and also used for designing of Resonant Reflector. At last, the Particle In Cell (PIC) method being used for estimating the interaction of beam and SWS to generate microwave power. It also estimates the output power and efficiency of the device.

**A. EMS Simulation**

In this set up, the normal modes of SWS are evaluated without beam and the dispersion curve is plotted by varying the phase of electromagnetic wave as shown in Fig. 2. Then the starting current of the single unit cell is calculated by imposing periodic boundary condition along the axis i.e., by considering infinite array of single unit cell [23]. The starting current vs frequency graph is depicted in Fig. 3.
many single unit cells required can be calculated. This can be extensively understood by Barkhausen criterion of oscillators [24].

B. TDS Simulation

This set up is used to test whether the estimated frequency of oscillation will sustain inside the SWS or not. Also, Resonant Reflector (RR) is designed by calculating the S-parameters corresponding to the frequency. The RR act as both pre-modulation cavity and reflector of the generated microwave towards extraction point. Pre-modulation of beam has an important role in enhancing efficiency [7, 10, 13, 25, 26]. Also, end reflector can be used at the end of SWS to enhance the efficiency and minimize the starting current of the device. The use of end reflector improves the beam coupling to the SWS by forming standing wave of relatively large amplitude [27, 28]. The use of end reflector is avoided in our case to prevent larger dimension of SWS which encourages further overbunching for certain input beam current.

S-parameter of RR has been plotted with logarithmic amplitude against a range of frequency and the blue line in Fig. 4. refers to the reflection coefficient ($S_{11}$) whereas the red one refers to the transmission coefficient ($S_{21}$). This can be clearly understood from the graph that at output microwave frequency the resonant reflector completely reflects the generated microwave field in forward direction. The RR has been resonated at $TM_{020}$ mode.

The non uniformity was introduced in both the period of SWS and the corrugation depth of the cavity to vary the interaction impedance along the axis of SWS. These structural variations lead to increase in efficiency [14, 15]. More the corrugation depth of cavity more will be the $Q$-factor. The main purpose of increasing $Q$-factor along the axis is to increase the electric field towards the end of SWS. The higher the field inside SWS, the higher will be the device’s interaction impedance and more energy will be transferred to the field from beam. The efficiency increment portion has been verified by Ref. 14 & depicted in Fig.5, while the field portion is validated by simulation and is depicted in Fig. 6.

![Efficiency vs. Time](image1)

**Figure 5. Temporal efficiency variation (a) Non-Uniform SWS (b) Uniform SWS**

Fig. 6(a) shows the electric field magnitude along the axis with uniform corrugation depth, whereas Fig. 6(b) shows the same for non-uniform corrugation depth. In uniform SWS, the $Q$-factor of each cavity is same and hence the energy extraction. But, what happens when the whole SWS is injected with limited energy, the preceding cavities stored more energy than the end cavity due to lack of energy availability towards end. Hence, the $Q$-factor should be increased gradually towards end to store more energy possible.

![Electric Field Variation](image2)

**Figure 6. Spatial Electric Field Variation along axis at Beam position (a) Uniform SWS (b) non-uniform SWS**

C. PIC Simulation

In PIC, Hexahedral mesh has been used with size one twentieth of the generated microwave wavelength. About 2 million macroparticles has been used for the electron emission from annular cathode surface through explosive emission model. The boundary condition $E_r=0$ has been kept at both transverse boundaries whereas axial boundaries kept open for the extraction of microwave.
The whole device is simulated to determine the output power and efficiency of the whole system by using CST Studio. In BWO, there is a chance that the reflected backward wave by RR which in turn becomes forward wave can interfere with the original backward wave. Therefore, the drift length (Length between RR & SWS) has been optimized for higher efficiency by observing the voltage pulse at RR through voltage monitor to see whether, the reflected forward wave interferes with the backward wave constructively or destructively. As we know, the beam transfers its energy to the microwave field by losing its kinetic energy, so the beam velocity gradually decreases along downstream. Therefore, in reference to the equation (4), the pitch or period of SWS should gradually decrease in order to maintain synchronism with the wave phase velocity.

Figure 7. Temporal Phase-space Plot of Electron Beam (a) 9 ns, (b) 9.2 ns, (c) 10 ns, (d) 11 ns & (e) 11.8 ns

The phase space plot of electron beam at different time is shown in Fig. 7 and how the beam gradually modulated in the presence of electromagnetic field can be understood. The beam first modulated, then due to the excess current gets overmodulated and starts to spread out due to Coulombic force as shown in Fig 7. How beam starts to modulate is shown in 7(a) & (b). One can see, at 10 ns 7(c), the beam starts to spread, at 11 ns 7(d), the beam starts to back stream and the beam completely loss synchronism at 11.8 ns 7(e).

Hence, further efficiency enhancement will not be possible. To reduce the backstreaming and overbunching or overmodulating, lowering the electron number density is one option. This phenomenon is pictorially shown in Fig. 8, which is easier to understand. Here, different color shows different energy range. The highest energy is referred to the red ones whereas lowest to the violet ones.

Figure 8. Beam Bunching & Backstreaming in Presence of Microwave inside BWO

V. SIMULATION RESULTS

Input 500 kV is supplied through a trapezoidal signal (red) as shown in Figure 9. Peak output power of 1800 MW has been observed (olive) with average output power of 810 MW (magenta). The beam current has been found to be about 6 kA. There is a time lag between the saturated input and saturated output power. The saturation time of microwave inside SWS is about 10 ns which can be clearly seen from Figure 9.

Figure 9. Input & Output Characteristic Graph of BWO

VI. CONCLUSION

A semicircular profiled BWO is designed to reduce field breakdown inside SWS with 5-unit cells of decreasing period, taking starting current consideration. This device has been subjected to 500 kV accelerating voltage through a rectangular pulse of 46 ns (Rise Time & Hold Time 2 ns & 44 ns respectively) in PIC simulation with 0.6 T guiding magnetic field. It has been found that the device efficiency is getting limited by the overbunching of electrons which leads to backstreaming. Backstreaming electrons loose synchronism with the backward wave and fall on the accelerating phase of forward wave and extracts energy from the field. This can be the reason for multipacting inside the SWS. The main cause of all the difficulties faced was found to be the excess beam current which was reduced by shrinking the cathode area.
Non-uniformity in both period and corrugation depth was implemented to increase efficiency. Phase space plot has been studied thoroughly to reduce the overlapping and backstreaming. Still more optimization in beam current is required for greater efficiency. Finally, 27% efficiency has been achieved with 500 kV and 6 kA input feed at 9.8 GHz frequency in pure TM_{01} mode.

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